A Novel Scheme to Search for Fractional Charge Particles in Low Energy Accelerator Experiments

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Abstract

In the Standard Model of particle physics, the quarks and anti-quarks have fractional charge equal to $\pm 1/3$ or $\pm 2/3$ of the electron's charge. There has been a large number of experiments searching for fractional charge, isolatable, elementary particles using a variety of methods, including e^+e^- collisions using dE/dx ionization energy loss measurements, but no evidence has been found to confirm existence of free fractional charge particles, which leads to the quark confinement theory. In this paper, a proposal to search for this kind particles is presented, which is based on the conservation law of four-momentum. Thanks to the CLEOc and BESIII detectors' large coverage, good particle identification, precision measurements of tracks' momenta and their large recorded data samples, these features make the scheme feasible in practice. The advantage of the scheme is independent of any theoretical models and sensitive for a small fraction of the quarks transitioning to the unconfinement phase from the confinement phase.

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In the Standard Model (SM) of particle physics, the mesons comprise two of quarks and anti-quarks and the baryons comprise three of quarks and anti-quarks, while the quarks and anti-quarks carry fractional charge $\pm 1/3e$ or $\pm 2/3e$, e being the magnitude of the electron charge[1]. The successes of SM in the fields of the spectroscopy and the high energy interaction of the hadrons have motivated a lot of experimental searches for fractional charge, isolatable, lepton-like particles. There has been a large number of experiments searching for free fractional charge particles using a variety of methods and no evidence up to date has been found to confirm their existence. There are three kinds of experiments used to search for fractional charge particles, which are based on the collision products of accelerator beams[3−6], cosmic rays[7], and bulk matters[8] respectively. No observation of fractional charge particles results in the confinement concept that the quarks are permanently confined within the hadrons. The questions are whether there is a small fraction of quarks transitioning to the unconfinement phase from the confinement phase and whether there are new sensitive methods to search for them.

It is noted that dE/dx ionization energy loss measurements are used to identify charged particle species for e^+e^-[3,4] (or proton anti-proton[5] or heavy ions[6]) collisions in accelerator based experiments. The energy loss fluctuation is described by Landau's theory[9]. One wonders if the theory is still valid for quarks, which take part in both the electroweak interaction and the strong interaction and is sensitive enough to distinguish the quarks from the five stable particles such as the electron, muon ,pion, kaon and proton if there is a small fraction of quarks which are unconfined. However it is no doubt that the conservation law of momentum and energy (four-momentum) applies to all kinds of interactions, which can be used to search for fractional charge particles in combination with the Lorentz force law for low energy accelerator experiments. The prerequisite for this kind of search is that a detector is required to possess large coverage, good particle identification, precise momentum resolution of charged tracks and energy resolution of neutral tracks and collect large data samples. For instance, recently upgraded CLEOc[10] and BESIII[11] detectors can search for fractional charge particles based on the laws. The center masses energy of the e^+e^- collisions in CLEOc and BESIII cover the energy range of the charmonium production. Therefore fractional charge particles in the mass range of 0 to 2 GeV can be conceived to appear in the products of the collisions if they are physical reality.

The momentum measurement of a track with charge qe produced in an e^+e^- event is

based its bending radius R in the magnetic field B along z direction in the tracking chamber according to the Lorentz force law,

$$P_{xy} = qeB/R,$$

where P_{xy} is the transverse component of the track momentum. The longitudinal component is measured by considering the polar angle θ of the track with respect to the e^+ beam direction,

$$P_z = P_{xy}\mathrm{ctg}(\theta).$$

In other words, the radius is a measured value while the momentum is a derived value and dependent on the assumed charge q. In the CELOc and BESIII experiments[10,11] as well as others[3–6] q is a priori set to be 1 no matter how large charge it has. The momentum $\vec{P}_{\mathrm{n}}$ measured in this way, we call it the nominal momentum, for the track equals to its real momentum $\vec{P}_{\mathrm{r}}$ if q is 1. If q is not 1, its nominal momentum changes by a factor of $1/q$ compared with its real momentum, i.e. $\vec{P}_{\mathrm{n}} = 1/q\vec{P}_{\mathrm{r}}$.

Hereafter q is assumed to be less than 1 for simplicity. For events with at least one particle of charge larger than 1, the similar analysis can be performed. Assuming there is a pair of quarks f and $\overline{f}$ with opposite charge qe in the event such as $\pi^+\pi^-u\overline{u}$, $K^+K^-d\overline{d}$ and $p\overline{p}s\overline{s}$, which is required to have even number of charged tracks. The total nominal momentum and energy are derived as

$$\begin{aligned}\vec{P}_{\mathrm{n}}(\mathrm{tot}) &= \vec{P}_{\mathrm{n}}(f) + \vec{P}_{\mathrm{n}}(\overline{f}) \ + \ \text{others} \\ &= 1/q\vec{P}_{\mathrm{r}}(f) + 1/q\vec{P}_{\mathrm{r}}(\overline{f}) \ + \ \text{others}\ , \\ E_{\mathrm{n}}(\mathrm{tot}) &= \sqrt{P_{\mathrm{n}^2}(f) + m_f^2} + \sqrt{P_{\mathrm{n}^2}(\overline{f}) + m_f^2} \ + \ \text{others} \\ &= \sqrt{(1/qP_{\mathrm{r}})^2(f) + m_f^2} + \sqrt{(1/qP_{\mathrm{r}})^2(\overline{f}) + m_f^2} \ + \ \text{others}.\end{aligned}$$

If $\vec{P}_{\mathrm{n}}(\mathrm{tot}) \neq 0$, there are two cases. One is that some tracks in the event are undetected for they are neutrinos or go beyond the coverage of the detector. Another is that q is not 1. For the latter case, q can be adjusted so that the real total momentum

$$\vec{P}_{\mathrm{r}}(\mathrm{tot}) = q\vec{P}_{\mathrm{n}}(f) + q\vec{P}_{\mathrm{n}}(\overline{f}) \ + \ \text{others} = 0.$$

Then the mass m_f of the quark (anti-quark) can be calculated by requiring the real total energy

$$E_{\mathrm{r}}(\mathrm{tot}) = \sqrt{(qP_{\mathrm{n}})^2(f) + m_f^2} + \sqrt{(qP_{\mathrm{n}})^2(\overline{f}) + m_f^2} \ + \ \text{others} = \sqrt{s},$$

there $\sqrt{s}$ is the mass center energy of the e^+e^- collisions. In practical measurement and calculation, one does not know which pair of particles with opposite charge have fractional charge. The momenta and mass of any one pair of particles with opposite charge can be adjusted so that the event satisfies the conservation law of momentum and energy. It should be noted that $\vec{P}_{\rm r}({\rm tot})$ is a vector with three components, one cpmponent can be used to derive q, the two others can be used to suppress events from the first case because they can not satisfy the conservation law of three components simultaneously while events with fractional charge particles can. The procedure is repeated for all events in the data sample and the parameter set of $(q,\ m_f)$ is obtained. Then the parameter set is plotted into a two dimension distribution. For the first case, $(q,\ m_f)$ are a set of random numbers, but for the latter case, they should concentrate at one or more points if there are one or more fractional charge particles in the data sample. If fractional charge particles carry continuum masses, they should concentrate along one or more lines.

To suppress the contribution to $(q,\ m_f)$ from the first case further, the velocity v_m of each of the pair of particles, which is measured by the detector, can be compared with the derived velocity $v_{\rm r} = qP_{\rm n}/\sqrt{m_f^2 + (qP_{\rm n})^2}$. They should be consistent, i.e. $v_{\rm r} - v_{\rm m} = 0$ if it is a real fractional charge particle. If the parameter set of $(q,\ v_{\rm r} - v_{\rm m})$ is plotted into two dimension distribution, the points corresponding to fractional charge particles should concentrate along q axis.

To search for events containing a pair of quarks $f1$ and $\overline{f}2$ with opposite charge qe and different masses m_{f1} and $m_{\overline{f}2}$ such $d\overline{s}$, the events are required to have even number of charged tracks. The total momentum, energy and one of the velocities

$$\vec{P}_{\rm r}({\rm tot}) = q\vec{P}_{\rm n}(f1) + q\vec{P}_{\rm n}(\overline{f}2)\ +\ \text{others}\ = 0,$$

$$E_{\rm r}({\rm tot}) = \sqrt{(qP_{\rm n})^2(f1) + m_{f1}^2} + \sqrt{(qP_{\rm n})^2(\overline{f}2) + m_{\overline{f}2}^2}\ +\ \text{others} = \sqrt{s},$$

$$v_{\rm r}(f1) = qP_{\rm n}/\sqrt{m_{f1}^2 + (qP_{\rm n})^2(f1)} = v_{\rm m}(f1)$$

are used to derive q, m_{f1} and $m_{\overline{f}_2}$. Another velocity $v_{\rm r}(\overline{f}2) = qP_{\rm n}/\sqrt{m_{\overline{f}2}^2 + (qP_{\rm n}/c)^2(\overline{f}2)} = v_{\rm m}(\overline{f}2)$ is used to suppress the contribution from the first case.

To search for events containing a pair of quarks $f1$ and $f2$ with same sign charge qe and $(1-q)e$ and different masses m_{f1} and m_{f2} such as $u\overline{d}$ and $u\overline{s}$, the events are required to

have odd number of charged tracks. The total momentum, energy and one of the velocities

$$\vec{P}_{\rm r}(\text{tot}) = q\vec{P}_{\rm n}(f1) + (1-q)\vec{P}_{\rm n}(f2) \ + \ \text{others} = 0,$$

$$E_{\rm r}(\text{tot}) = \sqrt{(qP_{\rm n})^2(f1) + m_{f1}^2} + \sqrt{((1-q)P_{\rm n})^2(f2) + m_{f2}^2} \ + \ \text{others} = \sqrt{s},$$

$$v_{\rm r}(f1) = qP_{\rm n}/\sqrt{m_{f1}^2 + (qP_{\rm n})^2(f1)} = v_{\rm m}(f1)$$

are used to derive q, m_{f1} and m_{f_2}. Another velocity $v_{\rm r}(f2) = (1-q)P_{\rm n}/\sqrt{m_{f2}^2 + ((1-q)P_{\rm n})^2(f2)} = v_{\rm m}(f2)$ is used to suppress the contribution from the first case.

To search for a pair of quarks f and $\overline{f}$ with opposite charge qe in events with only two charge tracks,

$$E_{\rm r}(\text{tot}) = \sqrt{(qP_{\rm n})^2(f) + m_f^2} \ + \ \sqrt{(qP_{\rm n})^2(\overline{f}) + m_f^2} = \sqrt{s},$$

$$m_f = qP_{\rm n}(f)\sqrt{1 - v_{\rm m}^2(f)}/v_{\rm m}(f)$$

are used to derive q and m_f. Another velocity $v_{\rm r}(\overline{f}) = qP_{\rm n}/\sqrt{m_f^2 + (qP_{\rm n}/c)^2(\overline{f})} = v_{\rm m}(\overline{f})$ is used to suppress the contribution from the first case.

Search for events containing three free quarks or one free quark and one diquark can be done in the similar way. The two simplest examples are $\Delta^{++}\overline{uuu} \ + \ others$ and $\Delta^{-}\overline{ddd} \ + \ others$ and their charge conjugation, where Δ decays to $N\pi$.

To estimate the power of the technique above, it can be used to select fractional charge particles from a Monte Carlo sample set, which includes a signal sample and a background sample. In this article, 200 events of $\psi(2S) \to d\overline{d}J/\psi, \ J/\psi \to e^+e^-$ and 200 events of $\psi(2S) \to u\overline{u}J/\psi, \ J/\psi \to e^+e^-$ through BESIII detector simulation[11] construct the signal sample. The background sample is 40 million events of $\psi(2S)$ inclusive decays, in which each decay branching ratio is from the particle data group (PDG). d ($\overline{d}$) and u ($\overline{u}$) carry 1/3 and 2/3 of the electron charge respectively. Their masses are assumed to be 0.005, 0.025, 0.045, 0.065 and 0.085 GeV.

To pick up the signal events and suppress the background events, the events in the sample set are selected if they have four charge tracks with zero total charge. The scalar sum and the vector sum of the four tracks' momenta are required to larger than 3.8 GeV and larger than 0.12 GeV to remove the background events with normal four tracks. Then a pair of opposite charge tracks' momenta are adjusted by multiplying a factor of q so that the event

satisfy the momentum conservation. The events remain if the adjusted total momentum is less than 0.017 GeV, i.e.

$$P_{\rm r}(\text{tot}) = \sqrt{\sum_{i=x,\ y,\ z} (qp_i(f) + qp_i(\overline{f}) + p_i(e^+) + p_i(e^-))^2} < 0.017\ GeV,$$

Where f and $\overline{f}$ are supposed to be a pair of opposite fractional charge particles, $p(f)$, $p(\overline{f})$, $p(e^+)$ and $p(e^-)$ are measured momenta for the four tracks. If more than one pair of opposite charge tracks satisfy the requirement, the combination with minimal adjusted total momentum is chosen. The unadjusted pair is supposed to be a pair of e^+e^- and is required to have invariant mass $\mid m_{e^+e^-} - 3.097 \mid < 0.100\ GeV$. The electron (positron) track is required to have zero hit in the muon detector.

Instead to calculate the f and $\overline{f}$ masses, the masses squared are derived to be $m_f^2 = q^2p^2(f)(1 - v^2(f))/v^2(f)$, $m_{\overline{f}^2} = q^2p^2(\overline{f})(1 - v^2(\overline{f}))/v^2(\overline{f})$, where $v(f)$ and $v(\overline{f})$ are the measured velocities and often larger than 1 due to measurement errors.

Then the total energy is required to be $\mid E(\text{tot}) - 3.686 \mid < 0.15\ GeV$, where

$$E(\text{tot}) = \sqrt{(qp)^2(f) + m_f^2} + \sqrt{(qp)^2(\overline{f})\ +\ m_{\overline{f}}^2}\ +\ \sqrt{(p)^2(e^+) + m_{e^+}^2}\ +\ \sqrt{(p)^2(e^-) + m_{e^-}^2}.$$

The number of events for the remaining events as well as the measured charge q and mass m_f ($m_{\overline{f}}$) for the signal channels are listed in table 1 and table 2. The efficiency to select the first channel is larger than that of the second channel, because the d and $\overline{d}'s$ bending radiuses in the detector are two time those of the u and $\overline{u}$ if they carry the same real momentum and the d and $\overline{d}$ arrive at the subdetector of the flight time easier. The Fig. 1 shows the distribution of the charge q_d and Fig. 2 shows the scatter of the mass m_d ($m_{\overline{d}}$) versus the charge q_d. It can be seen from the two plots that the measured charge q_d concentrates at 0.333 and mass m_d concentrates 0.010 GeV for the channel $\psi(2S) \to d\overline{d}J/\psi$ with the input mass $m_d = 0.005\ GeV$. 22 events remain from the background sample, which are also plotted in Fig.1 and Fig. 2. There is only one event in the d charge window $\mid q_d - 0.333 \mid < 0.040$ and 4 events in the u charge window $\mid q_u - 0.666 \mid < 0.040$.

In summary, an inclusive sample can be divided into exclusive channels $n_1\pi s\ +\ n_2Ks\ +\ n_3ps\ +\ n_4e^+e^-s\ +\ n_5\mu^+\mu^-s\ +\ n_6\gamma s\ +\ n_7fs$, where f denotes a fractional charge particle. For a fractional charge track, its nominal momentum, derived by assuming its charge equal to 1 when it is reconstructed, increases by a factor $1/q$ compared with its real momentum. Then the nominal total momentum and energy for the event

Table 1 The measured charge q_d, mass m_d ($m_{\overline{d}}$) (GeV) and events for the channel $\psi(2S) \to d\overline{d}J/\psi$

input mass m_d	0.005	0.025	0.045	0.065	0.085
output mass m_d^2	$0.010^2 \pm 0.026^2$	$0.022^2 \pm 0.026^2$	$0.037^2 \pm 0.031^2$	$0.053^2 \pm 0.026^2$	$0.078^2 \pm 0.029^2$
charge q_d	0.339 ± 0.003	0.333 ± 0.002	0.333 ± 0.003	0.329 ± 0.003	0.323 ± 0.002
events	36	45	38	32	38

Table 2 The measured charge q_u, mass m_u ($m_{\overline{u}}$) (GeV) and events for the channel $\psi(2S) \to u\overline{u}J/\psi$

input mass m_u	0.005	0.025	0.045	0.065	0.085
output mass m_u^2	$0.016^2 \pm 0.031^2$	$0.033^2 \pm 0.029^2$	$0.044^2 \pm 0.031^2$	$0.064^2 \pm 0.029^2$	$0.072^2 \pm 0.024^2$
charge q_u	0.635 ± 0.006	0.662 ± 0.005	0.660 ± 0.004	0.654 ± 0.009	0.659 ± 0.004
events	28	24	33	32	27

containing this kind of tracks will not satisfy the conservation law, which can help find fractional charge particles described by the two parameters (q, m_f) by analyzing each exclusive channel. Between the two parameters, q is more sensitive than m_f. Whether the distribution of m_f concentrates at one or more points very well depends on the momentum resolution for charged tracks and the energy resolution for neutral tracks. The effect of $\mid 1/q - 1 \mid$ on the momentum for charged tracks is much larger than the resolutions. Let $q = 2/3$, then $\mid 1/q - 1 \mid$ is 50%, while the momentum resolution is 0.5% for charged tracks and 2.5% for neutral tracks for BESIII[11]. The larger $\mid 1/q - 1 \mid$ is, the more sensitive the method is to search for the fractional charge particles, especially for the type of $f\overline{f}$. Another advantage of the method is independence of any theory models. Even if fractional charge particles carry continuum masses, the method can be used to search for them, while the dE/dx ionization energy loss method is not adequate.

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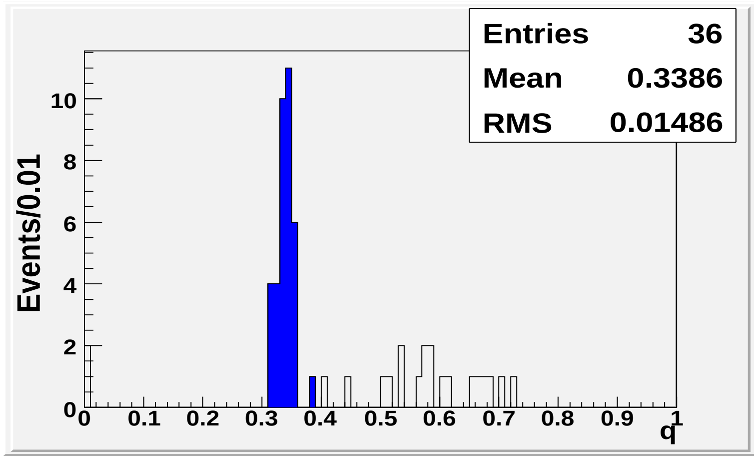

FIG. 1: The distribution of the measured charge q_d for $\psi(2S) \to d\bar{d}J/\psi,\ J/\psi \to e^+e^-$ with the input $m_d = 0.005\ GeV$. The shaded area is the signal events. The others are background events. The statistics is only for the signal events.

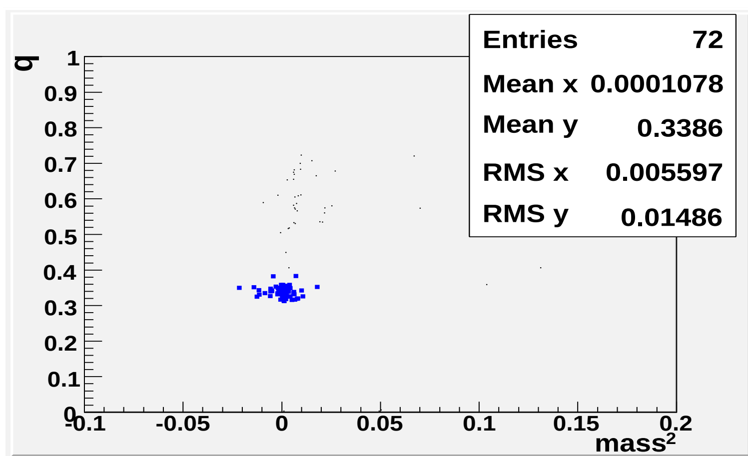

FIG. 2: The scatter of the measured m_d^2 versus the charge q_d for $\psi(2S) \to d\bar{d}J/\psi,\ J/\psi \to e^+e^-$ with the input $m_d = 0.005\ GeV$. The squares are the signal events. The others are background events. The statistics is only for the signal events.

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